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Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings

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ABSTRACT

The building stock in the world consumes approximately 40% of the energy and emits one third of the total greenhouse gases emissions (GHG). Improving the energy efficiency in buildings is vital to address the climate change and achieve energy independence (i.e. to become net-zero energy). Improving energy performance in existing buildings has been receiving significant attention recently, which entails reducing energy demand for building operations, without affecting the health and comfort of its occupants. This approach requires strategies beyond mere technical advancements. However, there is limited published literature which has comprehensively addressed these issues.

The aim of this paper is to critically review existing body-of-the-knowledge on improving energy efficiency of operating both commercial and institutional buildings. Peer-reviewed journal articles published from year 2000 to 2014 in reputed journals were reviewed. This review investigated contemporary energy efficiency approaches including technical, organizational, and behavioural changes. Based on the comprehensive literature review, a strategy map was developed as a pathway for achieving better building energy performance. It was noted that even though the existing studies predominately focused on technical advancements, approaches such as building behavioural changes have been largely overlooked. Findings of this study provide an important basis for setting up a national and organization wide strategy for improving the energy efficiency of commercial and institutional buildings.

Contents

Abbreviations: AC, alternating current; BIPVT, building integrated photovoltaic/thermal; BMP, best management practices; CAD, Canadian dollars; CHP, combined heating and power; CO_2, carbon dioxide; ERV, energy recovery ventilators; ETRC, Existential Technology Research Center; DC, direct current; DG, Distributed generation; GCHP, ground-coupled heat pumps; GHG, greenhouse gas emissions; GHP, ground-coupled heat pumps; HVAC, heating, ventilation, and air conditioning; LED, light emitting diode; LEED, leadership in energy & environmental design; PJ, peta joules; PV, photovoltaic; SSPCM, Shape-stabilized phase change material; TABS, thermally activated building systems

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1. Introduction

Commercial and institutional buildings are a key indicator of the socio-economic development of any nation. Despite numerous benefits to the society, dramatic environmental and social consequences are created throughout the life cycle of buildings [1,2]. The building stock in the world consumes approximately 40%, 25% and 40% of the energy, water and resources, and responsible for emitting one third of the total greenhouse gases emissions (GHG) [3]. Energy use forecasts show that in the future energy consumption portion of commercial buildings is expected to increase while the energy consumption portion of residential buildings is expected to decrease [4]. Commercial and institutional buildings create significant impact on social, environmental and economic sustainability. Statistics Canada reveled that in 2012, the total operational energy expenditure of commercial and institutional buildings exceed CAD 24 billion, which is ~3% of the Canadian gross domestic product [5]. The total energy use within commercial and institutional buildings was 1057 petajoules (PJ) which is 12% of the Canada's secondary energy use. Same buildings are responsible for emitting 11% of the total GHG emission in Canada [6]. Similar statistics are observed in other developed countries in the world. The heat discharged from the buildings in an urban settings creates the heat island effect, which is a noteworthy issue for urban centers in warm climates [7]. Apart from the aforementioned environmental and economic consequences, buildings create intense effect on the society. As an example, Canadians spend 90% of their time within buildings, by being involved in indoor activities [2].

Improving the energy efficiency of functional buildings is an important step in minimizing the environmental effects of the building stock [8]. The basic principle of the building energy efficiency is to use less energy for operations (i.e. for heating, cooling, lighting and other appliances), without impacting the health and comfort of its occupants. This approach would eventually reduce primary energy use and CO_2 [9,10]. Improving the energy efficiency of functional buildings entails many environmental and economic benefits such as reduced GHG emissions and operational cost savings [11].

Increased awareness on climate change, with other macro-economic changes (i.e., increase in energy prices, technology advancements) spurred the demand for high performing buildings that enable reduced energy use and costs, minimal use of natural resources and higher-quality indoor environment [9]. Environmental impacts of buildings are mainly determined from the life cycle impacts of building material and energy consumption during the operational phase [12]. Consequently, recent legislation and standards are pushing new construction towards sustainable and energy efficient buildings [9,13]. However, new buildings are only a small percentage of the national building stock. Therefore, improving the existing buildings provide the greatest opportunity for sustainable development [14].

Building energy efficiency is a popular stream of research in the recent past [8,15–23]. Energy performance of buildings can be improved using various techniques such as, through awareness programmes among building users [22], improving the building energy management [22], incorporating technical measures for the energy efficiency [22] and use of renewable energy [10,22–24]. In practise, a systematic technical and management change is required to achieve greater environmental and energy targets for the future [25]. Energy efficiency and resulting cost savings are created from the interaction among the behavioural, organizational and technological changes (Fig. 1). These elements and their interactions facilitate in achieving optimal and holistic energy performance targets [26].

However, the literature review and the industry analysis (e.g. energy efficiency retrofits used by public/private entities) show that, so far, building energy efficiency improvements projects have been conducted in ad hoc basis without a systematic decision making process [27]. The basic ground rules such as life cycle cost and building level of service have been neglected in many of present day energy efficiency improvement projects. Therefore, a consolidated knowledge base is required to inform the decision makers about the best course of action to suit their situation, prior to opting for detailed analysis for retrofit alternatives.

The objective of this article is to review the status of energy efficiency approaches available for operating buildings. Poor energy performance of existing buildings is a commonly observed issue around the world [28]. Hence, renovating the existing building stock is a main priority in improving the energy performance of building stock of a country [25]. It is important to have a combination of technologies to achieve superior energy performancce within buildings [29]. Zuo and Zhao, state that even though research on green buildings has expanded into various areas and contexts, still there is a lack of systematic review of the widespread knowledge [30]. The literature reviews on building energy efficiency can frequently be observed in the literature. However, as per researcher's knowledge there are no comprehensive studies specifically focused on improving energy performance of operating buildings.

This study looks at various energy efficiency approaches discussed in the literature with regards to commercial and institutional buildings. A systematic approach is adopted to identify relevant literature for this study. In addition, this research will show contemporary approaches and trending research areas with regards to energy efficacy of commercial and institutional buildings. This paper provides insights for industry practitioners and researchers who are keen on bringing about energy efficiency improvements in buildings and striving for green buildings.

2. Methodology

Keyword search in subject-specific databases is a commonly used and widely accepted methodology for review articles [31–34]. Hence, in this study "Compendex engineering village"

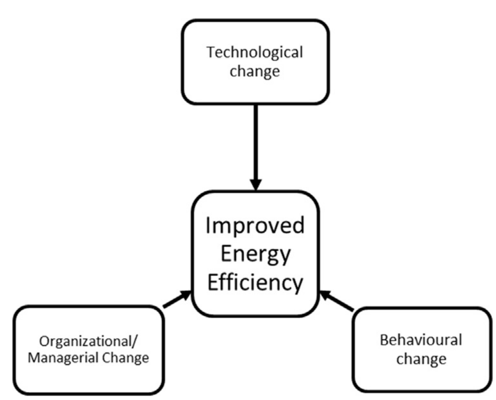

Fig. 1. Paradigms for energy performance improvement in existing buildings.

database was searched by using keywords combination "energy efficiency" and "commercial and institutional buildings". Since the objective of this study is to review up to date knowledge on energy efficiency, most recent studies from year 2000 to 2014 were retrieved.

This review has specifically considered journals with high impact factors. Journal impact factor mirrors the frequency of articles published in the journal being cited [35]. Despite its limitations, impact factor can be considered as an objective measure of the importance of the journal [36]. Five-year impact factors of the identified journals, with keyword searches on energy management and engineering ranged from 1.08 to 5.6. The median of the impact factors was 2.7. Therefore, impact factor threshold was set as 2.7 to filter the journals. Identified peer reviewed journals with the impact factor above 2.7 are as follows.

i. Energy policy
ii. Energy and buildings
iii. Energy Conversion and Management
iv. Solar energy
v. Renewable energy
vi. Energy
vii. Applied energy
viii. Renewable and Sustainable Energy Reviews

Due to the high impact factor, the above can be considered as high-quality journals. Hence, the literature review was restricted to the above-mentioned journals. The search criteria used in this study returned 122 journal articles.

Based on the study objectives, retrieved articles were categorized into the three paradigms of building energy efficiency (Fig. 1). Table 1 categorizes the main research topics associated with energy efficiency enhancement of commercial and institutional buildings during the past 15 years.

3. Technologies and assemblies

There have been many initiatives to improve the energy efficiency of operating buildings. In fact, from the mid 1990s, there has been an increase in energy efficiency patents granted for commercial and institutional buildings compared to residential buildings [37]. Published literature have proposed prolific methods, technologies and assemblies that reduce building energy consumption and improve the environmental performance. The above experimental approaches have a potential to achieve superior building energy performance targets in practise.

Components and systems are the key determinants in the overall energy performance of a building [38]. This section discusses the approaches for improving the energy performance of main building components (i.e. building envelope, lighting system, building mechanical systems).

3.1. Mechanical components

Heating, ventilation, and air conditioning (HVAC) system, is the highest energy consuming component in a building [39]. Main factors affecting the HVAC energy demand depends on the indoor temperature setpoint, air infiltration, window type, window-wall ratio, and internal loads [40]. In addition to that, influence of the above parameters are dependent on building type and climate [40]. Therefore improving the efficiency of HVAC system contributes in greater energy savings within the building [41]. Studies have identified that, proper selection and operation of HVAC systems can provide energy saving as much as 25% while maintaining acceptable indoor condition [42]. The literature defines 2 methods (i.e. passive and active measures) for reduction of HVAC energy demand [28]. Passive measures for HVAC energy efficiency includes, improving the existing building conditions such as replacement of windows, proper air tightness with adequate ventilation. Examples for active measures for energy demand reduction includes, upgrading or improving boilers and micro-generation through renewable energy sources. Several popular active technologies for energy efficiency discussed in the literature include, variable frequency-driven direct expansion air-conditioning systems [43], variable refrgenrant flow systems [44], use of programmable thermo stats [45], and inline heat pumps for water heating [46]. It is important that, these measures should not forego thermal comfort needs of the occupants (i.e. temperature control and humidity control) and indoor air quality [47–49].

Upgrading the existing mechanical system to an energy efficient technology is a possible route to improve the energy performance of existing buildings. Several examples are discussed below. Yik et al. [50] identified that converting from air-cooled to water-cooled air-conditioning systems enables significant electricity reductions [50]. Bruno identified that the use of dew point evaporative could reduce the space cooling energy demand by 52–56% compared to conventional systems [51]. According to Yu and Chan converting from head pressure control to condensing temperature control contributes in compressor power saving of 5.6–40.2% [52]. Chua et al. identified that use of innovative dehumidification approaches and better compression methods could improve the cooling system energy efficiency by 33% and the coefficient of performance by 20% [29]. A study by Fong et al. identified that optimizing the set points of water, and air supply temperatures in HVAC systems can provide monthly potential energy savings of 7% [53].

Chillers, chilled water pumps, and motors consume approximately 50% of the total energy use in commercial and institutional building [54,55]. Hence, energy efficiency of chilled water system is important for energy performance of commercial buildings [56]. Energy perfromance of chillers depends on the temperature of cooling water leaving the condenser, the temperature of supply chilled water and the load factor [54]. Some of the researchers identified that higher capacity mechanical systems reduce the payback period of the system [57]. However, Lee and Lee disagree with the claim that large chillers operating with higer percentage

Table 1
Overview of the literature.

Focus of the article	Description	Articles
Organizational/management paradigm (74)	These journal articles have focused on energy benchmarking, building energy audits, building energy characterization using mathematical methods, operation management of building components and development of methods to analyze factors affecting building energy.	[26,30,38–99]
Behaviour/operation paradigm (4)	These articles have focused on topics related to human behavior associated with building energy consumption including regulatory and voluntary approaches associated with operations.	[7,100–102]
Technical paradigm (50)	These articles have focused on various technologies, methods, programs that enable superior building energy performance. Some of these articles have studied the impact of energy retrofits and other external factors on building energy performance.	[28,103–159]

of the full capacity contributes in better energy performance [58]. Moreover, energy performance of a multiple-chiller system improves with a higher number of chillers [58]. Yu and Chan made a similar conclusion when they observed that a chiller plant with six chillers instead of four chillers pf equal size provided 10.1% electricity savings [59].

Utilizing the natural ventilation is a viable approach to improve the energy efficiency of the HVAC system [60]. Many air handling units in operation use air economizer cycle which provides free cooling under certain exterior air conditions [61,62]. Moreover, some of the studies conducted in the past have identified that night time ventilation reduces air conditioning loads in the summer [63]. However, designing and controlling natural ventilation system for a building is a complex task due to the stochastic nature of building interior (i.e. machine loads, occupancy) and exterior conditions (i.e. wind effect, temperature) [64]. A study by Wang and Song identified that optimal state in the air economizer cycle could be achieved through a universal control sequence with an additional airflow meter and temperature sensors (i.e. to measure supply air temperature and outside air temperature) [62].

Despite the potential energy savings, direct use of natural ventilation in a mechanically ventilation building minimizes the ability to control of indoor conditions [65]. Mixed mode buildings are an innovative approach to reduce the energy consumption and GHG emissions [66]. “Mixed mode” buildings use a hybrid approach to condition the building space through natural ventilation and mechanical ventilation [67]. Natural mode is used when outdoor conditions are suitable. Mechanical mode is used as a backup when outdoor conditions are not favorable [68]. Even though mixed mode ventilation suits various climates, implementation is hindered by various challenges such as lack of information, lack of understanding and safety concerns [66].

Heat and moisture recovery is a popular approach for improving the energy efficiency of HVAC system. Energy recovery ventilators (ERV) are used to transfer heat and moisture from exhaust air to outdoor fresh air resulting in significant energy savings [69]. Past studies have identified that energy saving performance of ERV depends on outdoor climatic conditions, the enthalpy efficiency, fan power consumption and fresh air change rate [69]. Many researchers have also studied the benefits of heat recovery systems. Roberts identified that the use of flat plate exchanger for incoming and outgoing air contribute in 70% heat recovery [28]. Another study by Wallin et al. revealed that retrofitting a traditional run-around coil heat recovery system could contribute in 65% heat recovery [70].

Shading effect in older and more established districts is a predominant factor for the HVAC system design. Ignoring this effect causes over design of HVAC (Cooling) system eventually increasing operational energy requirement [71]. However, present HVAC system designs do not consider shading effect from neighbouring buildings [71]. Lam studied the shading effect on commercial buildings in Hong Kong and identified that 25–31% of the energy use in buildings was due to not considering the shading effect in the HVAC design [71].

Even though building materials contributes to the thermal mass of buildings, the same rarely been considered for managing the energy performance. Thermal mass elements within new and existing buildings can be exploited to achieve desirable load-leveling and peak-shifting behaviors [72]. Thermally activated building systems (TABS) is an energy efficient and economically viable approach for building operation [73]. TABS use massive floors and ceilings for heat storage [73]. Compared to mechanical methods, this method is an economic approach to improve the building energy efficiency [72,73].

3.2. Lighting systems

Lighting system consumes approximately 15% of the total building energy demand [39]. Previous researchers have proposed numerous methods to improve the energy performance of the lighting system. These methods include, installing lamps with higher luminous efficacy, task based lighting design, daylight linked lighting systems and use of occupancy sensors for work areas [74]. Various factors that should be considered in selecting a feasible lighting source includes, power factor, output luminous flux, power required to operate, high current harmonic distortions, correlated color temperature, market price and color rendering index [75].

Converting to light emitting diode (LED) lighting system is a popular approach to improve energy performance of building lighting system [75,76]. However, Khan and Abas stressed the need for more awareness programs to spread LED lighting [75]. Likewise, more awareness programs should be conducted to inform building managers about the alternative approaches building lighting systems and adopting appropriate technologies.

Lighting control system is another important aspect of the lighting system. Factors that should be considered in determining the lighting control system include, behaviour pattern of the occupants, geometric properties of the room or building, daylight entrance and work performed [74]. Currently automated lighting have been largely overlooked in retrofit projects while the same is highly popular in new building constructions [74]. A large number of research studies have focused on automated the lighting systems, for instance Installing photo sensor lighting controls in day lit corridors can provide substantial energy savings [77]. Moreover, the use of day light sensors for electric lighting, use of energy efficient day lighting devices and appropriate ambient and task lighting could reduce lighting energy demand by 75–90% [78]. However, unreliability of light sensor systems has been identified as a challenge for gaining a market popularity [79]. Other challenges for automated lighting controls are high initial cost and complicated commissioning [74]. Ehrlich et al. proposed a solution that could accurately simulate photo sensor based lighting controls, which guides successful installation and operation, and reduce the need for expensive commissioning process [79].

3.3. Building envelope

Improved insulation reduces the heat loss or gain from the building and results in improving the thermal performance of the building envelope [63,76,80]. In fact, a study by Chua and Chou identified that there is a strong correlation between the annual cooling energy requirement and envelope thermal transfer value [81]. Many studies have focused on improving the energy performance of building envelope material. As an example, vacuum insulation panels enclose the building structure into an air tight envelope. Thermal performance of this technology is five times more effective than conventional insulation techniques [28]. Gagliano et al. identified that ventilated roofs with an insulation layer results in a cooling load reduction of approximately 50% [82]. Insulation effect can be created as farback from the construction phase. Yun et al. identified that the use of light weight aggregates glass bubbles, during the construction of the structure, reduces thermal conductivity [80]. However, not more than 20% glass should be used to satisfy structural properties [80].

Building fenestration geometry factors (i.e. window to wall ratio, window orientation, and room width to depth ratio) affect energy performance in all climate zones [83]. The energy savings achievable in hot climates through manipulating fenestration geometry factors is significantly high (approximately up to 14%)

while it is negligible for colder and temperate climate regions [83]. Due to its importance, sundry studies have focused on improving the fenestration features to improve building energy efficiency. Several examples for innovative windows include, vacuum glazing, triple glazing and use of aero gels [28]. Chow et al. identified that water-flow window provide significant reductions of air conditioning load and water heating loads. In fact, when compared with conventional double and single pane windows, water-flow window enables 32% and 52% heat gain reductions [84]. Several flaws of the above technology are energy requirement for water pumping and scarcity of water. Furthermore, replacing building transparent systems using polycarbonate enhances day lighting at a lower cost while achiving significant energy savings (i.e. by using multiwall polycarbonate panels) [85].

Building finishes such as paint can be used to improve the energy efficiency. Roberts identified that Insulating paints based on nano-technology enables improved thermal performance within the building. These paints possess low conduction based on the colour heat reflectivity compared to the conventional paints [28]. As an example, energy performance of buildings with high-reflectivity coating applied on the external surface performs better in locations where there are large temperature differences between daytime and nighttime [86]. When difference between day time temperature and night time temperature are smaller, buildings with interior insulation performs better [86].

Phase change material can be used to increase the insulation and thermal capacity of the building envelope [87,88]. Use of shape-stabilized phase change material (SSPCM) in the building envelope can exploit time-of-use utility rates by shifting the peak electrical loads to off-peak times [89]. A study by Zhu et al. identified that the use of SSPCM results in over 11% in electricity cost reduction and over 20% in peak load reduction [89].

Ventilated double skin facades for buildings have been gaining popularity in the recent past. Advantages of using double skin facades include, better ventilation, reduced heat loss during wintertime, improved acoustics and improved moisture and fire safety [90,91]. Zogou and Stapountzis studied the effect of using photovoltaics (PV) integrated double facades in south facing walls of office buildings [92]. The air gap between the backsides of the PV modules uses outdoor air to cool the PV modules which increases their efficiency. The heated outflow air can be used in the HVAC system as pre-heated air, which contribute in reducing the HVAC energy requirement [92]. However, only a building with high energy efficiency can benefit by double PV façade concept [92].

Lollini et al. observed a dynamic glazing system that can reduce energy use reductions in an office building [93]. A dynamic glazing system can be used in windows and curtain walls and contains triple glazed system with the possibility to mechanically ventilate the inner gap. Factors that should be considered in design, construction and management of a dynamic envelope component includes, building typologies, (i.e. defining an open system instead of a closed one) and ability to change the location parameters of a buildings [93]. Other innovative glazing technologies included automatic shading systems, electrocromic glazing and photochromic glazing [28]. However, validating new technologies and implementation of new technologies are identified as several main barriers associated with building energy efficiency [94].

3.4. Energy retrofitting and performance assessment

Building energy retrofits should reduce environmental impact (e.g., GHG emissions), gain economic benefits (e.g. improving energy performance, reducing fuel consumption), increase indoor comfort levels and improve architectural appearance [95,96]. Effective building retrofit design requires extensive analysis of all the alternatives including, linear, volumetric and material changes to the building, and exclusion of the obsolete building elements. External factors such as building orientation, location are equally important in selecting the retrofit methods [69,86,97]. Most importantly, optimal decisions with regards to building retrofits should receive the acceptance of all stakeholders [98]. Moreover, energy retrofits aim to optimize additional objectives such as environmental quality, life cycle cost, level of service, etc. Incorporating these additional objectives should be promoted through regulation, financing, redesigning existing programs and incentives [99].

As the first step of building energy retrofit projects, it is important to diagnose and analyze building energy consumption [41]. Thermal processes within a building are complex and difficult to understand, which makes manual calculations of building energy performance a difficult task. As a result, energy simulations are commonly used to detect abnormalities in building energy use and assess the effectiveness of available retrofit alternatives [28,100]. Moreover, researchers have stressed the importance of having accurate and simplified models for realistically calculating the energy performance of buildings [95,101].

There have been an increasing number of studies focused on building energy characterization. These studies provided innovative, simplified and cost effective methods to characterize building energy performance. Carlo and Lamberts have developed equations to classify building envelope efficiency [102]. Azar and Menassa have developed a framework to quantify energy saving potential from improved operation of commercial building systems [103]. Woo and Menassa have designed a virtual retrofit model for decision making with regards to building retrofits. This model has integrated theories and technologies such as building information modelling, building energy simulation, agent-based modeling and multi-criteria decision making with the aid of state-of-the-art software [98]. Menassa has developed a framework to evaluate investments for building retrofits considering uncertainties in costs and benefits and to achieve optimal investment strategies [104]. Also, several countries around the world have developed country specific building energy performance assessment tools (e.g., [101,105])

Accuracy of the energy simulation results for commercial and institutional buildings is a much-discussed topic in the literature. Researchers maintain that usually there is a discrepancy between simulation data and the actual data [28]. Bhandari et al. stressed the importance of the accuracy of energy data especially when it is used for energy assessment and calibration [106]. The use of less accurate data in design forces over estimation of equipment size which is a major setback for building performance [107]. A study conducted in Hong Kong revealed that the use of realistic design data enabled 6–22% increase in building energy efficiency [104].

Incorporating energy-saving measures in existing buildings is a major challenge [108]. Common barriers for building retrofit projects identified in literature include, lack of funding, lack of interoperability, and unstructured decision-making [98,109,110]. Moreover, despite numerous policy instruments aimed at improving building energy efficiency, the pace of innovations is deemed inadequate [37]. Altwies and Nemet identified pertaining reasons for the aforementioned problem as, insufficient information, disjointed decision-making, principal-agent problems, and lack of learning from dissimilar projects [37].

3.5. Micro generation using renewable energy sources

Numerous authors have stressed the importance of using renewable energy to improve the environmental performance of commercial buildings [111]. Findings associated with renewable energy use within commercial and institutional buildings are discussed below:

Multifunctional renewable energy based elements are a lucrative method in achieving high performing buildings [112]. Building integrated photovoltaic thermal (BIPVT) systems are desirable features of urban buildings that generate electricity and hot water. These features could be installed in the building as retrofits [113]. A study by Ibrahim et al. identified that BIPVT system improves building energy efficiency from 73% to 81%. However the energy saving potential of this method is not yet fully utilized [113]. Further improvements are required on energy efficiency, cost reduction and building integrated application of BIPVT features [114]. Building integrated photovoltaic panels (BPIV) windows enable significant energy savings in commercial and institutional buildings [115]. In order to maximize building energy performance, it is important to customize the BIPV features according to the location characteristics [116]. Existential Technology Research Center (ETRC), located in downtown Toronto, Canada has incorporated several multifunctional BPIV systems such as flexible solar membrane, solar awnings, solar louvre and solar outdoor lab space which produces energy while supporting the occupant behaviour [109].

Distributed generation (DG) and combined heating and power (CHP) systems are expected to play a major role in future buildings, by reducing GHG emissions and minimizing the operational cost [117–120]. A study in Thailand identified that building level CHP plants would enable primary energy saving of 3.2% from 2003 levels [121]. Chua et al. identified that combined cooling heating and power plants improve thermal and electrical efficiency approximately by 70% [29]. Naimaster et al. observed that the solid oxide fuel cell CHP plants allow 7.5–14% utility cost reductions and more than 50% of reduction in the GHG emissions [120]. Designing DG/tri-generation systems should consider building and location parameters. As an example solid oxide fuel cell CHP plants are well suited for colder climates [120]. Huang et al. identified that tri-generation system with a bio mass gasifier would suit commercial and institutional buildings with low heat to energy ratio (approximately 0.5–0.75) [122,123].

Use of hybrid technologies in building level improves the energy and environmental performance [74,124]. Despite its high cost, hybrid technologies are one of the best approaches for reducing the carbon footprint of buildings [124]. Studies show that the solar thermal is one of the most cost-effective approaches for space heating [124]. Ground-coupled heat pumps (GCHP) are a viable method for both cold and hot weather regions as a heating/cooling method for commercial and institutional buildings [125,126]. A hybrid GCHP systems (e.g. solar-assisted with a latent heat energy storage tank) could improve the coefficient of performance of the building heating system [126].

Building owners should consider renewable energy after having incorporated all possible energy conservation measures [108,127,128]. A study by Yalcintas and Kaya demonstrated that energy efficiency measures are approximately 50% or more cost-effective compared to photovoltaic systems [128]. Hence, it is important that federal and provincial policy makers opt for policies that require energy efficiency measures mandatory for any incentive payments for renewable energy sources [128]. Also, it is important to focus merely beyond micro-generation and identify other technical aspects associated with renewable energy technologies. As an example, installing direct current (DC) circuits for the lighting system in grid connected and PV powered buildings could reduce annual costs by 2–21% compared to similar system with AC circuits [129]. Therefore, Authorities should establish safety regulations and standards for these innovative approaches [129].

There are several barriers associated with micro-generation in the building level. The main barrier for micro-generation in building level using renewable resources is the high upfront cost. Other barriers for micro-generation include, lack of reliability of the technologies, uncertainty of the fuel supply (e.g. bio fuel) and uncertain pricing structure are [110].

4. Building energy management

Many researchers have emphasised the importance of adopting organizational changes to improve the energy efficiency of buildings [41,53,130,131]. The published literature reviewed revealed four important attributes associated with building energy management, namely, building commissioning, energy monitoring, energy benchmarking and standardization include energy labelling. The following sections discuss these attributes in detail.

Real-time energy monitoring is vital in improving the building energy performance [41,132]. Energy metering is commonly used for life cycle management of the building energy performance [41,131]. Energy metering helps in diagnosing issues with building energy use when there is a significant discrepancy between metered value and the anticipated value [131]. Futuremore, having energy sub meters facilitate closer monitoring of secondary energy consumption [133]. In order to achieive the above, researchers have emphasised the importance of effective and scientific measures to monitor the building energy use [41]. Standard design guidelines and regulations are required to guide the design and installation of energy sub-meters in commercial buildings [133].

Modern energy codes require installation of advanced features such as daylight sensors and occupancy sensors [134]. A study by Kamilaris et al. [135] revealed that, real-time monitoring and behavioural change could influence 40% of the building energy use in terms of savings [135]. Smart meters allow building users to see daily energy consumption patterns and encourage changes in behaviour patterns to reduce the peak demand [28]. In fact, a study in California showed that peak demand can be reduced by 13% when customers were warned about peak energy rates. Building zone level control considering personalized occupancy patterns is another viable approach for reducing energy consumption within buildings. In fact, studies revealed that user profile based control could reduce HVAC related energy use as much as 8% in an office building [136]. The future of energy metering and fault detection requires smart building equipment with sensors that enables central control and remote monitoring [78,134].

Energy codes provide valuable guidance to manage and improve the energy performance of buildings [137,138]. Several studies have been conducted to determine the benefits of using energy codes. For instance, Tulsyan et al. studied the energy saving potential of using energy code in India, and identified energy saving potential through the use of the energy code from 17 to 42% [134]. Lee and Yik mentioned that if building energy code was made mandatory, annual electricity consumption in Hong Kong can be reduced by 7.9% [139]. A study by Radi showed that approximately 7% of electricity demand reduction could be achieved by using the energy codes in Bahrain [137].

Building commissioning is important, but remains a neglected area in building energy management. This approach helps to reduce energy consumption by streamlining the systems [140]. However, benefits of commissioning fade over the years [140]. As a solution, Bynum et al. have developed a fault detection and diagnostic tool to support building commissioning (i.e. Automated Building Commissioning Analysis Tool) [140]. Similarly, Du et al. developed neural networks based tool to ensure fault detection in commercial buildings [141].

Establishing building energy consumption quota is a beneficial method in measuring the building energy consumption and use it as a basis for examining the impact of energy retrofits [142]. Energy consumption quota could be used as the threshold to assess the building energy efficiency. Also, the same could be used to impose penalties for the energy users who exceed the energy quota and provide incentives for those who use energy below the quota. However, more research is required to study the effective energy standards and benchmarks for buildings.

Energy benchmarking defines a value that represents typical energy use, which will be used as the baseline against which building is compared [143,144]. Moreover, energy benchmarking improves the energy efficiency and transparency of energy consumption, promotes competition among institutions, established baseline for energy labelling programs and helps to investigate reasons for poor energy performance [143,145,146]. Researchers have proposed numerous approaches for benchmarking a building energy use. For instance, Borgstein and Lamberts proposed a energy benchmarking method considering statistical data and energy audit data [145]. Chung, considered a fuzzy based linear regression model for energy benchmarking [143]. Chung et al. used energy use intensities, building age, occupants behaviour, occupancy, maintenance procedures, indoor temperature set-point and installations to set energy use benchmarks [146]. Martin developed energy benchmarks considering energy use intensities [144].

Building energy labelling programs can be observed around the world (e.g. LEED, Energy Star etc.). LEED, which is the most popular building rating system, is available for operating buildings. LEED certified facilities enable 34% energy savings compared to conventional buildings [147]. Similarly, a study revealed that Hong Kong Building Environmental Assessment Method is having a potential to achieve 32% energy savings from the current levels [139]. Furthermore other building rating systems and programs such as Energy Star (US based), EN15251 (European Union) has also gained popularity in the past few decades [148]. Success of energy labelling programs are critically dependent on its partnerships and alliances [149]. As an example success of Energy Star was partially due to its partnership with federal, regional, state, and local programs. In addition to energy savings, energy labels facilitate in claiming subsidies for energy tariffs. For example LEED certified buildings in India gain energy tariff subsidies [147].

Despite their numerous benefits, impacts of building labeling tools have not reached the expected level. This issue is mainly because strict technical requirements stipulated by the building rating programs are not sufficient to improve the energy efficiency single-handedly [150]. In addition, major building rating systems predominantly focus on building design that makes these rating systems more suited for new buildings [145]. In order to reinforce energy efficient building practices, rating systems should focus more on performance (i.e. operation and maintenance) rather than material specifications [151].

There are several organizational barriers associated with building energy management. Studies show that buildings owned by non-profit groups are less energy efficient compared to private buildings [130]. Several other organizational barriers affecting building energy management include volatile energy prices, meeting regulation, making a business case (i.e. difficulty in showing the monetary impact of behavioural changes) for and establishing operational best practises [94].

5. Occupancy and operational requirements

Many researchers have agreed that behaviour and lifestyle choices are important criteria in reducing building energy demand [27,28,40,152,103]. Previous studies have identified that, buildings that caters to a customer-base who spend considerable time on-site have a high likelihood of displaying energy inefficiencies [130]. Therefore, it is important to move beyond the technical changes and explore alternative approaches such as behavioural changes to achieve superior energy performance [152].

Improved building energy performance requires cooperation of all the stakeholders [111]. Escrivá-Escrivá observed that even the actions of the non-specialized technical workers can significantly affect the building energy performance [153]. AnJanda emphasised the importance of inter-disciplinary understanding of organizational culture, occupant behaviour, and technology adoption is required to set up occupancy/operation best practises [152]. Moreover, cooperative efforts are required to establish energy efficiency culture, identify opportunities for low-carbon operations and to execute proposed solutions by the management [111]. The following are the seven basic actions that can contribute in reducing the energy use in buildings [153].

i. Accurate measurement of the operational energy usage and record keeping: This action is required to identify energy over-consumption and savings.
ii. Schedule building processes and maintaining a diary: This action can contribute in deployment of facilities according to user requirements while adhering to electricity utility contract.
iii. Automatic monitoring of electricity energy consumption: This feature enables building managers to repair or solve malfunctions in the event of an electricity consumption increase.
iv. Assign to an individual the responsibility to monitor energy consumption: The responsibility to individual would ensure better management of building energy consumption.
v. Pro-active measure to improve the building energy efficiency: This action would support proper management of the building stock.
vi. Training building users: Provide easier understanding and control of building energy system for the building users. Intensive awareness programs would reinforce energy efficiency efforts at the organizational level [111].
vii. Promote communication: Promote communication between managers and users to interact and exchange information for facilitating optimal use of facilities.

Roberts identified that building occupants are more forgiving of thermal discomforts if they are provided with control to alter it [28]. Ability of zone control and occupancy measurements enables significant energy savings while creating minimal impact on the thermal comfort [154]. Sun et al. [155] developed a demand limiting strategy that optimizes monthly cost savings while maintaining acceptable indoor conditions through adjusting the indoor temperaure set point. This approach was able to save monthly energy cost up to 8.5% [155]. Maheshwari et al. identified that the use of programmable thermostats in an institutional building in Kuwait enabled 25% energy savings [45].

Some of the researchers have stressed the difficulty in measuring the effectiveness of energy management practices and behavioural changes in commercial buildings [103]. Furthermore, research on improving building energy performance has scarcely focused on how new approaches should be implemented in practise including socio-technical frameworks associated with them [152]. As a solution, Zhou et al. have developed a distributed energy resource choice and operations program which is capable of finding the optimal combination of installed equipment considering the utility tariffs, thermal loads and available equipment, which enables reducing the carbon emissions of the buildings [156]. Due to political challenges, gaining the support of users for occupancy reforms is an important hurdle [92,5,4]. Other, barriers

Table 2
Summary of energy efficiency improvement initiatives.

Energy performance enhancement initiative		Advantages	Challenges
Technologies and assemblies	**Mechanical components**		
	• Converting/Upgrading the existing HVAC system (e.g. upgrading chillers etc.)	• Produce significant energy savings	• Disruptive to the building occupants • High cost of installation
	• Use of natural ventilation for cooling	• Provide healthy breathing air to the occupants	• Use of natural ventilation depends on the outdoor conditions / season • Difficulty to comply with energy code requirements.
	• Heat and moisture recovery (e.g. energy recovery ventilators, enthalpy exchangers)	• Produce significant energy savings	• Performance of the system depends on outdoor conditions
	Lighting system		
	• Installing state-of-the-art lighting methods (e.g. LED lighting etc.)	• Low cost retrofit method	• Lack of awareness with facilities managers
	• Installing sensors / automated lighting controls	• Reduces lighting energy demand.	• Complicated commissioning • Unreliability of light sensor systems with users • High initial cost and complicated commissioning
	Building envelope and micro-generation		
	• Use of thermal mass elements inside the building	• Shifting the peak power demand • Energy load levelling • Low-cost, easy to implement approach	• Limited impact on the overall building energy usage
	• Changing building fenestration geometry	• Produce significant heating/ cooling energy savings • Could reduce lighting energy demand.	• Disruptive to the building occupants • High cost of construction/ installation
	• Upgrading the building envelope (e.g. Ventilated double skin facades etc.)	• Produce significant heating/ cooling energy savings	• Complexity of validation and implementation of new technologies • Validating new technologies and implementation of new technologies
	• Building level micro-generation (e.g. CHP)	• Significant improvements in thermal and electrical efficiency	• High cost of installation
		Enhances the aesthetics of the building (e.g. building integrated photovoltaics)	• Lack of reliability of the technologies and uncertainty of the fuel supply
Energy management	• Energy monitoring, energy benchmarking and standardization • Building commissioning	• Help to diagnose issues with building energy use • Facilitate in claiming subsidies and energy rebates • Reduce energy consumption by streamlining building systems	• Lack of standard design guidelines and regulations to guide the design and installation of energy sub-meters • Lack of attention provided by facilities managers.
Occupancy and operational requirements	• Establish energy efficiency culture in an organization.	• Involve nominal costs for organizing	• Gaining the support of users for occupancy reforms is an important hurdle

associated with improving building operations include managing demand response, demonstrating success of energy efficiency programs and improving energy performance [94]. Table 2 summerizes advntages and challenges of implementing energy performance alternatives.

6. Road map

The information gathered in this review was developed as strategy map to improve building energy efficiency. Road map illustrates the sequence of value creation within an organization. The goal of this strategy map is to abate building energy demand and promote sustainable operation. This method shows the sequential stepwise connections between objectives to gain a superior energy performance within the building. As shown in the level, energy performance vision of owners or the top management provides the organization to set the foundation for improved building energy performance. Second, the tactical management integrates the vision to the daily operations by means of best management practices (BMPs) and continuously monitor them. The tactical management should observe and respond to irregularities and publicize the success of energy efficiency improvements. As the third level, building users should alter the behavioral patterns according BMPs. This strategy would create value for the organization by fostering environmental wellbeing, economic benefits, and improved organizational image as depicted

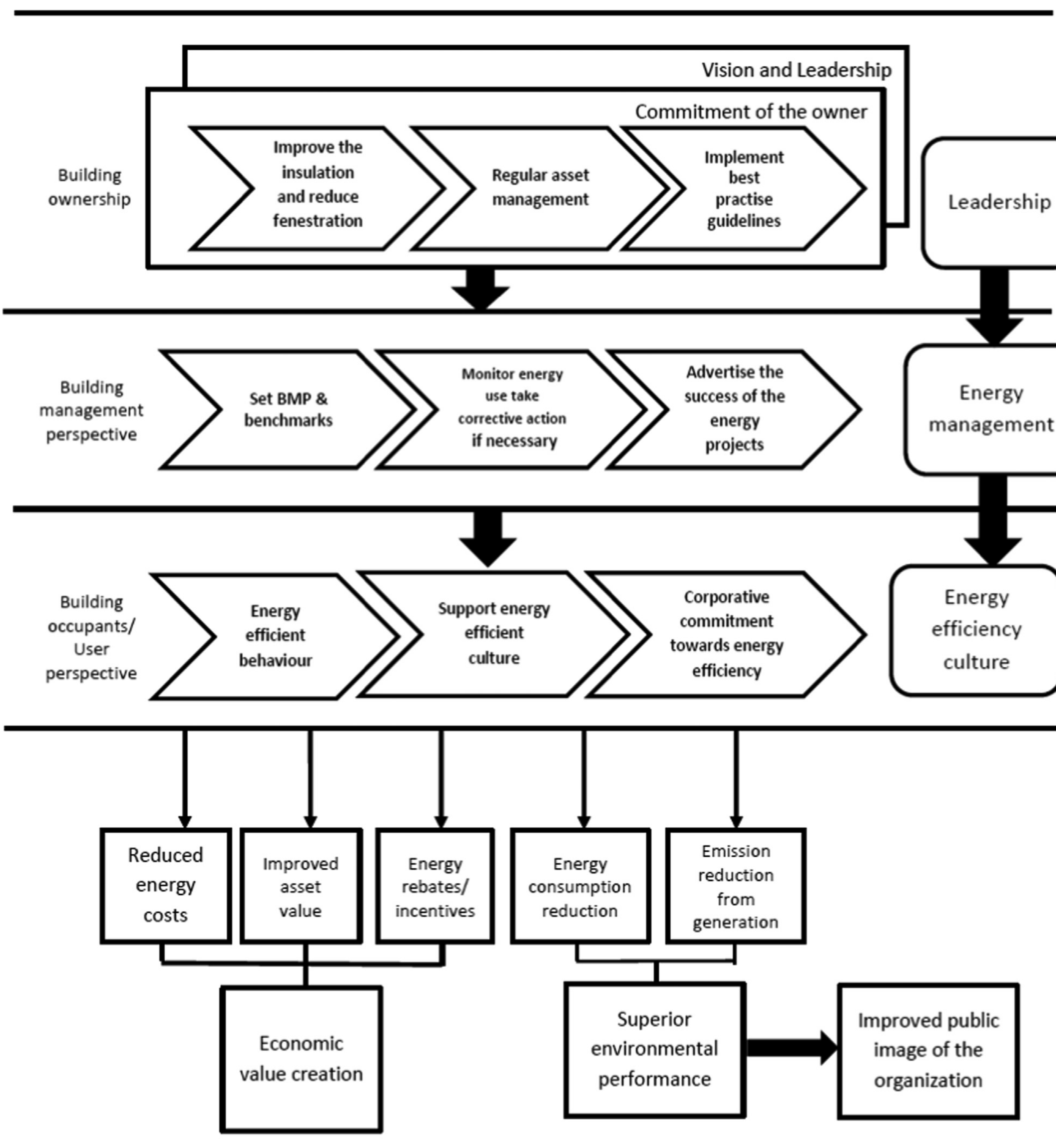

Fig. 2. A road map for improving building energy operations.

in the top levels. Fig. 2 illustrates the strategy map for improving the energy performance of operating buildings.

7. Discussion

This study conducted a critical review of the literature on energy efficiency enhancement approaches for operating buildings. This study focuses on, technologies and assemblies to improve the building energy performance, building energy management approaches, occupancy and operation specific requirements to enhance building energy performance.

Currently, building professionals and researchers are keen on designing and developing net zero buildings and net positive buildings. Moreover, in recent times there has been a pressure for converting older buildings into more energy efficient. Consequently, there has been an upward trend in innovations related to building energy performance. This trend could be due to escalating energy prices, adoption of building codes, building energy labelling and advancements in the information technology. Studies show that building energy efficiency improvements entail lower risks and higher returns compared to other financial investments such as stocks and government bonds [157]. Hence, life cycle costs and energy performance can become marketing criteria for commercial buildings [132].

Improving the energy efficiency should follow a structured process. There should be energy efficiency promotion, reducing energy consumption, alternative energy production, and improving the social awareness through private initiatives and supported by government intervention. Furthermore, it is important to seek beyond the common methods and identify the state-of-the-art technologies. Several examples for the future vision by commercial and institutional buildings include, smart facades (facade adopts according to climate and environment), intelligent buildings, new insulating materials which are cost effective and aesthetically acceptable, high-performance windows and micro-generation etc. [78,112].

Glass facade buildings have been a popular architectural consideration in the recent past. A major portion of the façade is glazed with high transmittance glazing that result in poor thermal performance [158]. A large number of technologies have been adopted to improve the performance of the glazed buildings such as solar control facades, daylighting facades, active facades, double skin facades and natural ventilation. Above measures are associated with several side effects. For example, highly glazed double skin façade buildings are affected by unwanted heat gains in the summer consequently demanding high air conditioning load [159]. Moreover, use of tinted glasses increase the lighting energy consumption of the building [160].

Recent studies identified that long term exposure to blue or ultra-violent lighting can cause several health concerns such as potential changes in melatonin production, disruption of human sleep cycles and risk of damage to retinal cells [161–163]. LED lighting produces a fair amount of lighting in the blue spectrum and do not emit ultra-violet rays [161,162]. Further research is required to assess the human health risk of prolonged exposure to LED and other energy efficient lighting.

Installation of more energy efficient equipment or renewable energy systems does not fully achieve expected carbon reduction or energy reduction targets. Building operations is an important determinant in reducing the energy footprint of commercial and institutional buildings. Even though the final decision on building energy improvements rests with the owner, smart use of energy and eliminating environmental and energy waste is an approach that could be adopted with zero cost. Therefore, building managers could ensure better energy performance within buildings via retrofits, commissioning, decommissioning and cultivating best practices in building operations among the building users.

So far, limited studies have focused on the rebound effect of energy consumption due to a reduction in energy cost. Increase in energy demand could trade-off the benefits of energy cost reduction [155]. Therefore, it is vital to look at the potential of human actions to improve the energy efficiency of commercial buildings that are expected to gain high interest in the future [103,103,100] (Azar and Menassa, 2014) [53,54,56,57]. This research should focus on examining, experimenting, and optimizing different energy management strategies and occupancy interventions for commercial and institutional buildings [103].

Increase of atmospheric temperature due to global warming has adversely affected energy performance, indoor air quality, thermal comfort and sustainability of commercial buildings [164]. The current and future building should be capable of adapting to the changes in local climatic conditions throughout the building service life [164]. It is predicted that more cooling and less heating will be required in the future. As an example a study in Australia identified that from 2020 to 2080 due to the climate change building energy consumption would change from −0.6% to 8.3% and cooling equipment capacity should increase by 9.1–25% [165]. Hence, more accurate weather data considering future patterns can be an important determinant in future building designs.

There are multiple equipment operating in a building simultaneously. The general perception is that there are interactions among equipment energy consumption as well as changing climates and indoor conditions [76]. However, studies showed that the reduction of lighting energy doesnot create a significant impact on HVAC energy for commercial and institutional buildings [166].

Achieving the future energy efficiency targets require vigorous implementation of policies such as strengthening the building codes, adopting efficiency standards, labelling of office equipment and restructuring the heat metering and pricing structure [103,167]. There should be best practise standards for more controlled and systematic building energy usage. Moreover, governments should support operation focused on energy management programs in commercial buildings [103]. As an example Canada had updated energy code to improve the energy performance in commercial and institutional sector [25]. It is important that regulators ensure compliance to the energy code and maintenance in the long term. Moreover, in order to ensure compliance with the national energy code for buildings, it is important to update conventional regulatory approval processes and publicize the benefits of energy efficient buildings [138]. Further research is required to develop and execute policy instruments.

Informed decision making is vital for improving the energy performance of existing buildings. These decisions are reinforced by information, incentives, knowledge and access to capital [78]. However, currently lack of information and know-how is a clear obstacle for energy efficiency enhancement projects [75]. Above identified barrier curtails selecting for the optimal decision with regards to building energy efficiency. In addition, lack of information blinds the building owners to pursue potential funding sources for building energy improvements. Current approaches such as utility energy service contracts, energy savings performance contracts and on-site renewable power purchase agreements are innovative solutions to those who lack initial funding. In addition to the funding, these approaches provide expert technical knowledge for energy efficiency enhancements.

When performing building energy management, it is imperative for building energy managers to receive required data from various sources in a format suitable for building managers [168]. The availability of multiple information sources eliminate the need for subjective judgement or expert intervention with respect to holistic performance analysis. Moreover, it is important that quality control procedures are in place to ensure the accuracy of the data.

Importance of energy audits is an important initiative for the building energy management. A comprehensive energy audit should consider environmental profile, occupants behaviour and energy devices used in the building [135]. Energy audits determine the energy performance assessment of the building by a credible third party. This approach is important for authorities when implementing carbon taxes. Moreover, periodic energy audits provide an objective basis for the building performance assessment and rating.

8. Summary

This study conducted a comprehensive review of contemporary approaches for improving the energy performance of operating commercial and institutional buildings. The review was based on articles published during the past 15 years in the high-quality journals on energy engineering and management.

According to the published literature, there are a large number of approaches available for improving the energy performance of operating buildings. It is evident from the literature that that there is a considerable need for studies that are focused on behavioural specific improvements. Hence, future studies can focus on behavioral based approaches in improving the building energy performance. Further research is required to understand how organizations develop energy management best practises and implement them. Moreover, safety risks, design, installation, and regulatory barriers associated with innovative technologies should be studied before there are used in practise.

Building energy system is comprised with several components, which determines the energy performance of the building. Due to deterioration, these components would perform below its expected level. Therefore, asset management frameworks should be in place to improve the energy performance of buildings. As per the authors knowledge there are no comprehensive studies focused on building asset management. In the future, asset management would be a rewarding approach for improving the life cycle performance of commercial and institutional buildings.

Future research areas with respect to building energy efficiency include, metering and control systems, measures to ensure low cost thermally comfortable and productive environments, state-of-the-art equipment and technologies that provide heating, cooling and electricity with lower carbon footprint. Enhanced use of information technology, improved sensors, real-time monitoring and automated decision-making systems would support building energy management in an innovative way. Therefore, it is important to peruse further research in the life cycle performance, implementation and cost factors associated with aforementioned approaches.

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